Self-Organization, Emergence and Multi-Agent Systems

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Abstract—We begin by describing the importance of emergence in industry and the need, in certain situations, to move away from a reduction mind-set to a more holist approach. We define the term emergence in context of self-organizing systems, autopoiesis and chaotic systems. We then examine a field that is commonly used to explore emergence and self-organization, namely agent and multi-agent systems. After an overview of this field, we highlight the most appropriate aspects of agent research used in aiding the understanding of emergence. We conclude with an example of our recent research where we measure agent emergent performance and flexibility and relate it to the make-up of the agent organization.

Index Terms—**Complexity theory, self-organizing systems, chaos, emergence, autopoiesis, reductionism, agents, MAS.**

I. Introduction & Background

Many natural systems show structure or organization at a macro level. Examples of such systems include galaxies, planetary systems, cells, organisms and societies. Traditional scientific fields attempt to explain these features by referencing the micro properties or laws applicable to their component parts, for example gravitation or chemical bonds. Science, and physics in particular, has developed out of this Newtonian paradigm of mechanics. In this world-view, every phenomenon observed can be reduced to a collection of atoms or particles, whose movement is governed by the deterministic laws of nature – this approach is called reductionism. Through this model, little room is left for the explanation of the spontaneous emergence of self-organization that has been observed in a multitude of systems including life itself [6].

Whilst this reductionist view is an enormously useful way of looking at the intricate relation between simplicity and complexity, it is increasingly argued that this view is incomplete and that the reductionist view is but a part of a larger "mechanism" that results in complexity [6]. We observe the low level laws of nature but, in some important cases, lack the understanding of how they give rise to the observed behaviors at the highest organizational levels. To fill in the gaps in the reductionist view, the subject of complexity and emergence must be approached in a holist manner looking for system properties applicable to all such collections of parts, regardless of size or nature.

However, this way of looking at systems is at odds with traditional engineering methodologies where reductionism is at the forefront of problem solving. This poses a problem when one considers the trends companies will increasingly face with regards to increasing interactivity and complexity across manufacturing, product and support domains [19]; understanding how one complex component works is relatively straightforward – understanding how it will perform with countless other devices is a far greater challenge [7].

This is not just a problem in the hi-tech and aerospace industries [8]; it is a wider problem [5]. Complexity produces unpredictable results from the interactions of a whole host of actions which, by themselves, seem simple. The 2001 UK fuel crisis can be cited as a simple example, where a protest outside a few oil refineries almost shut down the whole country with astonishing swiftness. The same is true for computer viruses, diseases affecting the food supply chain, failing transportation networks, etc [5, 25]. Stewart opines, "Efficiency… means that every conceivable component is just about to break down… The big problem here is reductionist managers operating with a complex system as if it were simple." [25]

This emphasizes that as society and technology becomes increasingly interconnected and reliant on distant resources, the problems of complexity will come to the fore. Ironically, the only time it is appreciated how complex a system is, is when it fails. Because of this, it is engineers, and to some extent management, who will be first having to deal with complexity head-on in real life situations.

Intrinsic to the holist view is the concept of emergence, where beneficial or indeed detrimental behavior emerges from local interactions. This emergence is found in flocking behaviors such as crowd surging, the spontaneous collapse of distributed networks and increased market volatility [25]. In industry applications such as distributed control architectures, this emergent behavior is typically unintended and often detrimental. Examples include well documented telecommunications outages where router software upgrades, having passed scaled-down test-bed examinations, malfunctioned in real life causing large scale outages. Router timing errors only emerged during fully operational interactions, something test-bed examinations did not pick up, as they were orders of magnitude smaller [10].

Not all emergent behavior is unfavorable; positive emergence is found in ant path planning, bird flocking and the Internet [6, 18]. Examples of positive emergence in industry include ant-foraging inspired routing of telephone calls [4] and adaptive insect behavior based car painting [26].

This critical issue of understanding, mitigating and exploiting emergence can be applied not only to products but to entire systems and even organizations that exhibit high levels of interactivity and complexity. To explore these questions, we utilize Multi Agent Systems (MAS), discussed in a later section.

There is some confusion and lack of clarity around the various definitions surrounding emergence. As such, the following section provides an overview of this field.

II. Complexity, Self-Organization & Emergence

A relatively new research field called Complexity Theory has emerged, stating: "Critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties" [20].

Complexity theory includes the new study of Self-Organizing Systems (SOS). The order we see around us is only a small sub-set of the theoretically possible order. So why don't we see more variety? The study of SOS aims to shed some light to this perplexing question [13].

Before the widespread use of computer technology, researchers in this field had to rely on analytical methods. Now, however, by creating mathematical models and running computer simulations, it is possible to quickly explore large numbers of possible starting positions and to analyze the common features that result. The field of self-organization, therefore, seeks general rules about the growth and evolution of systemic structure, the forms it might take, and finally methods that predict the future organization that will result from changes made to the underlying components. The results are expected to be applicable to all other systems exhibiting similar network characteristics [20].

It has been suggested that there is an intrinsic link between the second law of thermodynamics and the formation of structure and self-organization. Perhaps the most obvious example is life which is a form of "dissipative structures" – a term coined by the Belgian thermodynamicist Ilya Prigogine [33]. Such systems continuously generate entropy, but this entropy is actively dissipated, or exported, out of the system. Thus, it manages to increase its own organization at the expense of the order in the environment [13].

However, the export of entropy does not explain how or why self-organization takes place. Prigogine [33] noted that such self-organization typically takes place in non-linear systems, which are far from their thermodynamic equilibrium state. Here, the thermodynamicists' concrete observations of physical systems are complemented by the more abstract, high-level analysis of complex, autonomous systems in cybernetics.

What is interesting to note is that the concept of a SOS has changed over time; the British cybernetician W. Ross Ashby proposed what he called "the principle of self-organization" [3]. He noted that a dynamic system, independent of its type or composition, always tends to evolve towards a state of equilibrium, more commonly called an attractor. This reduces the uncertainty we have about the system's state, and therefore the system's statistical entropy, which is equivalent to self-organization [13].

An attractor, in general, is a region of state space that "attracts" all nearby points as time passes. Attractors are of crucial importance because they capture long-term dynamic behavior of a complex system [6]. An attractor provides a lower dimensional representation of a system's dynamics, which in some ways immediately implies that there is some from of self-organization taking place. Typically, an attractor can be a point, a regular path, a complex sequence of states or an infinite sequence called a "strange attractor". All specify a restricted volume of the system's phase space. The ratio of the volume of the basin to the volume of the attractor can be used as a measure of the degree of self-organization present. This Self-Organization Factor (SOF) will vary from the total size of state space for totally ordered systems where there is maximum compression, to '1' for when there is total disorder and zero compression [20].

Interestingly, even though the physical dynamics of a chaotic system is unpredictable, there are certain aspects of the system that can be predicted, as it will always follow the path of an attractor [36]. It must be noted that the tendency to think that dynamic systems are therefore goal orientated must be resisted; dynamic systems do not seek out the attractor. The only way of determining the attractor's characteristic is by studying, or simulating approximately, the system for a sufficient time in order for the attractor to appear.

Since entropy can be shown to be a function of the attractor's dimension [35], the smaller the dimension of the attractor, the smaller the entropy and hence the higher the order [35]. This property has been used to measure the level of emergence, produced by Wright [40].

It is our opinion that the distinction between self-organization and emergence is blurred and not universally separated in the literature. For example, Daniel Hillis states that "Sometimes a system with many simple components will exhibit a behavior of the whole that seems more organized than the behavior of the individual parts" – paraphrased, the whole is greater than the sum of the parts. This, according to Hillis, is known as emergence [14].

It has also been stated that emergent properties will typically be found unexpectedly and then explained from the ground up. In very complex systems however, starting conditions and complex interactions render precise explanations very difficult, with simulation used in an attempt to find patterns or generalities that go some way to explain the observed emergent behavior. In such cases, emergent properties are nested layers in a complete system and one must look at the top level for an explanation, rather that from the bottom level constituent parts [6].

Looking at these definitions, the concept of emergence is practically identical to that of Self-Organizing Systems. However, one can place a distinction between SOS and emergence, where the above statements still hold.

Emergent behaviors in complex systems are not always beneficial. The AT&T long-distance telecommunications crash mentioned earlier exemplifies this. On the other hand, one can say that self-organization is a specific and ‘good’ emergent behavior in that it increases the fitness of the system in solving ‘the problem’, however that may be defined.

A more quantitative definition defines self organized behavior as one where the dynamical systems attractor of the behavior of n agents has an intermediate value. That is, an attractor dimension of between ‘1’, where all agents acting synchronously and a number related to n, indicating totally dissociated behavior [40].

Emergence is associated with the capability of this self organization to change drastically, in response to a change in the environment (e.g., the ability of a school of fish to dissociate as a predator passes through, and then quickly reform into a self organized state). Note that this is not so much a definition of emergence, as it is a characteristic of systems that demonstrate emergence.

We therefore argue the terms emergence and self-organization are as follows: Emergence is a sometimes negative phenomena found in complex systems, which can also be positively exploited to varying degrees. The full, or ultimate, positive exploitation of emergence is self-organization; a system aligns itself to a problem and is self-sustaining, even when the environment changes. Thus, the term “self-organization” refers to a specific form of emergence.

As this discussion is broadly defined by terms and semantics, it is appropriate to dwell briefly on the aspect of a “self-sustaining” system. Maturana and Varela coined the term autopoiesis to characterize those systems which (a) maintain their defining organization throughout a history of environmental perturbation and structural change and (b) regenerate their components in the course of their operation [24]. Note that the first condition is a general property of a SOS, whereas the second is a more specific subset meriting a specific label – autopoiesis. Self-Organizing Systems maintain their organization, but do not necessarily regenerate their own components [39].

It is also useful to define the term “chaotic” in the context of emergent behavior. While the popular press uses the term “chaotic” informally to describe emergent behavior in general, the distinctive feature of emergent behavior is that it can appear unexpectedly from the interactions of explicitly designed components. The formal definition of “chaotic” is one particular form of emergent behavior with specific distinguishing characteristics (e.g., sensitive dependence on initial conditions, a white noise power spectrum, and a trajectory in the phase space that does not intersect itself, occupies non-zero but finite volume, and has a fractal structure) [32].

In any given system, emergence – the appearance of an unexpected property – is, in general, proportional to the complexity of a system. These unexpected properties can appear, disappear and alter as the complexity of a system changes. However, a self-organizing system is more robust and scalable. In such systems, as complexity increases, the initially unexpected property (such as the global behavior of an ant colony) is maintained. This can only occur after an initial threshold; two ants will not exhibit the emergent behavior found in a large ant nest, but once a certain critical mass is reached, the global behavior emerges and is sustained with increasing ant colony size. It is this requirement for a point of criticality that suggests to us that self-organization is a specific form of emergence.

Agents are often enthusiastically cited by academia and, of late, industrial analysts as a means to understanding and exploiting beneficial emergence and as a solution to increasing complexity, informational entropy and man-machine interactivity. These issues are different and require different types of agents. After looking at agents as a global field, we focus on the examination and implementation of emergent organizations in academic and industrial domains. These are predominantly explored through a subset of the agent systems paradigm termed Multi-Agent Systems.

III. AGENTS AND MULTI-AGENT SYSTEMS

The concept of an agent is not new; the Artificial Intelligence (AI) community started looking at symbolic reasoning “agents”, from 1956-1985. However, problems with symbolic reasoning lead to a reaction against this, the so-called reactive agents movement, from 1985-present, through the use of parallel AI and was coined Multi-Agent Systems (MAS). However, the AI systems approach places much greater emphasis on the AI element than agent systems do, with the key differences between AI and agent systems being autonomy and communication. Ultimately, the AI project aims to build systems that can understand natural language, recognize and understand scenes as well as thinking cognitively. However, when agent systems are built, the requirement is for a system that can choose the correct action within a very limited domain; paraphrased, “a little intelligence can go a long way”.

Many attributes that are required for a system to be called an agent have been suggested. Requirements such as physical presence, mobility, social ability and abilities that are even more specific have been cited, but it is clear that no concise definition will emerge, as the term has now encompassed too many fields. However, looking at the requirements for a single agent, one main theme has emerged, namely the ability to be autonomous. By being autonomous, an agent has the capability of exhibiting control over its internal state and its external actions on its environment. Over the years, various definitions of what an agent is have regularly appeared in publications; including:

The IBM Agent – “Intelligent agents are software entities that carry out some set of operations on behalf of a user or another program with some degree of independence or autonomy, and in doing so, employ some knowledge or representation of the user’s goals or desires.” Intelligent agents act for another, with authority granted by the other [1].

The Maes Agent – “Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed” [22].

The Artificial Intelligence: a Modern Approach (AIMA) Agent – “An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors” [38].

Jennings et al Agent – “An encapsulated computer system that is situated in some environment and that is capable of flexible action in that environment in order to meet its design objectives” [16].

While there are similarities between these definitions, it is difficult to make the case that they are defining the same entity. We can conclude that the term “agent” does not hold an agreed universal definition which raises some concern. Furthermore, the above definitions can be expanded in various manners. The best quoted example of such expansion is the Jennings *et al*. definition. The key to this definition is the word “flexible”. Nwana provides another interesting and in our opinion more intuitive approach to what is an agent; an agent should have at least one of the following properties namely co-operation, learning and autonomy [27]. Combinations of two criteria allow agents to perform in a different manner. An agent possessing all three attributes is defined as “smart”.

In addition, Van Parunk argues convincingly that by emphasizing the plurality of agents, the focus ought to be shifted from designing ((***intelligent agent***) *systems*) to (*intelligent* (***agent systems***)) [31]. This is a fundamental point to consider – a collection of dumb agents is often better suited to a problem than a single smart one [15]. This may initially seem to be counterintuitive, but as agents get smarter, their functionality in fact reduces [31]. As such, the focus of industry which will face emergent issues outlined earlier ought to focus on the social aspect of agent systems – Multi-Agent Systems. Hence, when designing MAS, much more consideration has to be given to agent interactions and not just individual agent actions. We therefore define MAS as: *a collection of autonomous, social actors where, through local interaction and social communication, emergent global behavior occurs.*

Since becoming a buzz word in 1994, the concept of agent and MAS-based computing has stirred wide enthusiasm and, sometimes, hype within the research community [28]. Two highly quoted papers emerged that year; “Intelligent Agents: The New Revolution in Software” by the respected UK based market research company Ovum [11], and “Agents that Reduce Work and Information Overload” by Maes [21]. The former predicted that “agents will generate $2.6 billion in revenue by the year 2000” and the latter, still regularly quoted as backing for the agent paradigm, predicted informational entropy as a future issue and agents as the solution. Maes went as far as stating that agent systems could change our life style. These predictions, extrapolating future needs (e.g. dynamic conference itinerary booking) with potential agent based solutions, have patently failed to materialize ten years on. Reading such predications and theories on how agent systems would operate, with little or no discussion on how they would be implemented was common at the commencement of agent research. Nwana’s paper addressed the reasons why the above agent scenarios were a challenge from an implementation perspective at the time. Paprzycki [29] examines Nwana’s discussion in [28] and compares issues raised in 1999 with the current (2005) state of research. A key theme in that discussion is that much has yet to be done in the agent domain to fulfill the early promises and hype in the late ‘90s [30].

These white papers and articles championed the potential benefits agents could bring to industry and how they would revolutionize the way business is carried out. This implies a leap in technological capabilities. Intel’s Andy Grove talks about inflection points that force companies to revisit their core strategies due to technological advances. However, these inflection points are very rare, so managers can become weary of hype [12] so it is important to examine whether businesses are falling for “agent-hype” or whether agents will indeed cause a true technological inflection point leading to significant benefits to business [34].

Radjou from Forrester Research explores this question, albeit from the narrow perspective of Customer Relationship Management (CRM) and supply chain agency. He states that "Trading networks today are collapsing under the disruptive influence of new business drivers, such as" [34]:

Outsourcing – The farming out of business processes is now taking place in industries across the board: for instance, Ford out-sources more than 50% of their engineering, whereas Nike out-sources 80% of its manufacturing to the Far East;

Shortening product life-cycles – The average market life-cycle of a branded drug is less than a year. Rapid prototyping is helping reduce time to market for complex products;

Fickle demand – This has to do with the growing empowerment of consumers who are using the Internet to choose which products they want, and dictate when and where they want them to be delivered.

To Radjou's list we would also add:

Service business model – industry is increasingly moving towards charging clients for use of products, while retaining ownership and maintenance obligations. Examples of this include software as well as hardware such as aircraft components. A publicized example is General Electric's (GE) "power by the hour" engine. Sensors monitor the engine's performance on a real time basis and send the information via satellite to an earth station that analyses the data and compares it against an experience data base. This information is used to identify current problems, predict future problems and schedule maintenance. As a result of this capability, GE is selling power by the hour rather than selling engines. Running a fleet with 60% less assets, their service revenue has increased from $600 million to well over a billion dollars [37];

Mass customization – consumers have increasing product customization options afforded to them, which is subsequently implemented at the assembly stage rather than being pulled out of stock [17].

These business drivers can create a big imbalance between supply and demand, leading to uncertainty and volatility. Radjou argues that organizations are now facing a reality where flexibility rather than efficiency will lead to a competitive advantage. It is interesting that this observation was made by Stewart [25], discussed earlier, from a slightly different and perhaps more accurate perspective; Organizations that are seen as "efficient" by management are actually teetering on the brink of perpetual collapse. This is especially the case when large organizations have been designed around static environments but are now having to deal with current industrial realities. Thus, flexibility and robustness are actually contemporary components of a true efficiency metric – given an organization's operating environment (static, dynamic), how efficient is the organization in terms of its flexibility and adaptability?

If it is accepted that flexibility will be a key driving force for business, and there are many compelling arguments for such an assessment, we need to question whether traditional technologies are suited to a dynamic environment. Looking at existing supply chain processes and the software used, the focus is on traditional efficiency rather than flexibility. In implementation terms, this translates to hub and spoke data architectures where the centralized hub attempts to proactively sense and respond to problematic changes in the network [23]. Critically, by denying a degree of autonomy to the spokes (suppliers), multiple problems have to be processed centrally rather than being dealt with at the source. Such an approach typically leads to an escalation of the problem due to the time delay and lack of knowledge and experience at a local level that suppliers take would take for granted [34]. Thus, as the need for high connectivity, flexibility, decentralization and autonomy increase so will the application of agent technology and the agency methodology. This potential uptake would be linked to the centrality of the application domain and the exposure to variability.

We have also examined how industry perceives agency, and concluded that one of the prime agent drivers will be the need for increased flexibility. Thus, if flexibility gains will account for most of a company's competitive advantage and agent technology can provide increased flexibility there is a need to put together convincing business cases based on flexibility gains, and most relevant to our discussion thread, be able to measure and quantify flexibility [2], a topic discussed briefly in our conclusions.

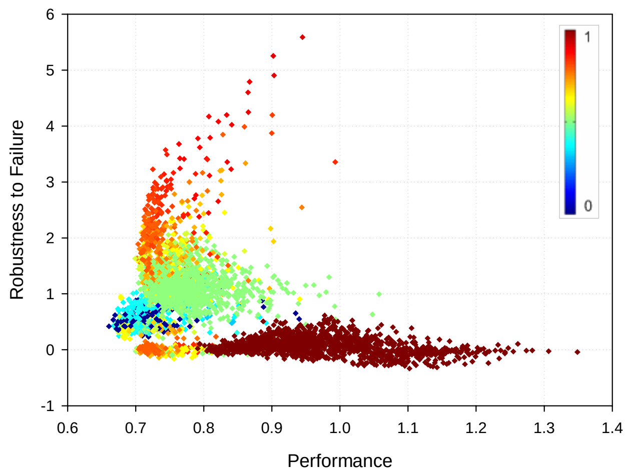

Fig. 1 Robustness to failure versus performance versus organizational attribute shown on the color scale (agent function specialization)

Our chief aims are to attain a better understanding of emergent global behavior in organizations and consequently, improve their design, and the design process itself. These aims are addressed through the use of MAS simulations of organizations. Our research program has already developed a set of structural and performance metrics that, in part, aid the understanding of flexibility – a key issue discussed above [9]. Fig. 1 shows the performance (traditionally known as efficiency) of various different MAS organizations against the robustness of the organization to agent failure (a form of flexibility). The color points are a structural metric used to describe the social aspect of the organization. Use such methods it is possible to discern key emergent organizational types.

IV. Conclusions

We have studied emergence in the context of Self-Organizing Systems, chaotic systems and autopoiesis. Furthermore, we have outlined a definition of agent systems and discussed the state of the agent field vis-à-vis the original agent vision in the late ‘90s. Taking a commercial view of the utility of agent systems, we conclude that the issue of flexibility, which is tied into the issue of emergence and complexity, ought to be a key driver for agent research in industry.

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